A METHOD TO REPAIR LOCALIZED AMPLITUDE DEFECTS IN A EUV LITHOGRAPHY MASK BLANK

BY

Daniel G. Stearns   (USA)

1641 Dallas Ct.

Los Altos, CA 94024

Donald W. Sweeney   (USA)

1568 Aria Ct

Livermore, CA 94550

Paul B. Mirkarimi   (USA)

2155 Kilkare Rd.

Sunol, CA 94586

Henry N. Chapman   (UK)

1312 Melanie Way

Livermore, CA 94550

5

A METHOD TO REPAIR LOCALIZED AMPLITUDE DEFECTS IN A EUV

LITHOGRAPHY MASK BLANK

10   The United States Government has rights in this invention pursuant to

Contract No. W-7405-ENG-48 between the United States Department of Energy

and the University of California for the operation of Lawrence Livermore

National Laboratory.

15   BACKGROUND OF THE INVENTION

Field of the Invention

        The present invention relates to minimizing defects in the components

produced by an extreme ultraviolet lithography (EUVL) system, and more

specifically, it relates to a method for repairing amplitude defects in an EUVL

20   mask blank.

Description of Related Art

Extreme ultraviolet lithography (EUVL) is a technology that employs projection optics to print integrated circuit patterns on silicon wafers at a wavelength of light of approximately 13 nm. Since absorption is high in all materials at this wavelength, the EUVL optics including the mask must be reflective. The EUVL reflective mask blank consists of a thick glass substrate that is first coated with a reflective multilayer film, and then coated with an absorber layer that is subsequently patterned. See C.W. Gwyn et al., J. Vac. Sci. Technol. B 16, 3142 (1998), S. Burkhart et al., Proc. SPIE, vol. 3676, p.570, 1999 and T. Ikeda et al., "Reflection Type Mask", U.S. Patent No. 5,052,033, granted 09/24/91.

Any defects in the reflective coating or absorber layer are problematic since they produce printing errors in the integrated circuit pattern on the wafer. The basic strategy is to develop extremely clean processes for fabricating the EUVL masks that minimize, and even eliminate, the defect population. However, trends in the current manufacturing of lithography masks suggest that there will be a cost benefit in developing a viable capability to repair a small number of defects on the EUVL mask. The classification (10) of defects that can occur in a EUVL mask is outlined in Figure 1. Repair methods must be developed for all types of defects.

Referring to Figure 1, defects (12) in the patterned absorber layer consist of regions where metal is unintentionally remaining or missing. These

- 3 -

cause errors in the local amplitude of the reflected field, and hence are

"amplitude defects". There currently exists a mature technology for repairing

defects in the absorber layer of lithography masks that work in transmission. It is

reasonable to expect that this technology, based on milling and deposition using

5   a focused ion beam, can be extended to repair defects in the absorber layer of

EUVL masks. See T. Liang et al., J. Vac. Sci. Technol. B 18, 3216 (2000).

Referring still to Figure 1, a problem unique to EUVL masks is the

existence of defects (14) in the reflective multilayer coating. The prototypical

multilayer coating consists of 60 bilayers of molybdenum and amorphous silicon.

10   The thicknesses of the individual layers are approximately 3 and 4 nm for the

molybdenum and silicon, respectively. The reflectivity is a resonant property of

the coating whereby the fields reflected by every pair of layers interfere

constructively. Thus the reflectivity occurs through the depth of the film, and any

deformation or disruption of the layer structure within the reflective coating can

15   become a defect.

The classification of defects in the reflective multilayer coating

naturally divides into two categories, as indicated in Figure 1. The first category

is the intrinsic-type defect (16). The intrinsic defect is nucleated by the statistical

fluctuations that are characteristic of the vapor deposition process that is used to

20   deposit the multilayer film. In particular, there is shot noise in the atom-by-atom

deposition process that leads to the accumulation of random roughness. The

variance of the roughness scales fairly linearly with the total thickness of the

coating. The lower frequency components of the roughness are efficiently

replicated by overlying layers and thereby propagate up towards the top of the

coating. When one of these random thickness fluctuations exceeds a critical size

5   that is approximately 0.5 nm in height and 100 nm in width, it becomes an

intrinsic defect. The resulting deformation of the layer structure produces an

unacceptable perturbation in the phase of the reflected field. Hence intrinsic

defects are "phase defects".

The second category of defect in the reflective multilayer coating is the

10   extrinsic-type defect (18) as shown in Figure 1. The extrinsic defect is a

deformation or disruption of the multilayer structure nucleated by an external

perturbation. This could be a particle, pit or scratch on the mask substrate, a

particle imbedded in the multilayer film during the deposition process, or a

particle, pit or scratch imbedded on the top of the coating after deposition. As

15   indicated in Figure 1, the effect of the defect on the reflected field will depend on

where the defect is nucleated. When the nucleation occurs at the substrate (20), or

in the bottom part of the multilayer coating (22), then the film growth dynamics

will tend to damp out the structural perturbation, so that the top layers are

deformed but not disrupted. In this case the defect produces a modulation of the

20   phase of the reflected field, and is a "phase defect". The other possibility is that

the defect is nucleated near or at the top of the multilayer coating (24). This

could be a particle introduced during the deposition of the top layers, or a

particle, pit or scratch imbedded in the top surface subsequent to the deposition.

The particle and the damaged part of the multilayer coating will shadow the

underlying layers and thereby attenuate the reflected field. Hence these are

5   "amplitude defects".

U.S. Patent No. 5,272,744, titled "Reflection Mask", granted 12/21/93

by Itou et al. describes a special reticle for x-ray and extreme ultraviolet

lithography in order to facilitate the repair of multilayer defects. This reticle is

comprised of two multilayer film stacks separated by an Au layer and is in

10   contrast to the conventional reticle design incorporating patterned absorber

layers on a multilayer film or the other design of a patterned multilayer on an

absorber, as described in U.S. Patent No. 5,052,033, titled "Reflection Type Mask"

by T. Ikeda et al., granted 09/24/91. There are some disadvantages to the Itou et

al. approach, including (i) their reticle is more difficult and expensive to fabricate

15   than other designs, (ii) the introduction of the Au layer will likely introduce

additional roughness in the reflective overlayer, reducing the reflectance and

throughput of the lithography system, (iii) their repair process is not a local one,

and involves covering the entire reticle blank with resist, etc, which could lead to

new particulates/defects, and (iv) it is uncertain whether their method will work

20   in a practical sense since it requires extreme control of the Au deposition and

various etching processes so that a phase defect does not result from the

multilayer defect repair process.

U.S. Patent Application Serial No. 09/669,390, titled "Repair of

Localized Defects in Multilayer-Coated Reticle Blanks for Extreme Ultraviolet

5   Lithography", by the present inventors, filed 9/26/00 and incorporated herein

by reference, discloses techniques for repairing multilayer phase defects in EUVL

reticles. These techniques utilize a focused energetic beam to induce a

contraction in a localized area of the multilayer. When the multilayer structure is

significantly disturbed, the defective multilayer alters the amplitude as well as

10   the phase of the reflected EUV light, and the defect is then designated as an

"amplitude defect". The above technique would not be effective for repairing

amplitude defects in EUVL reticles; the repair of amplitude defects in EUVL

reticles is the subject of this invention.

It is important to develop methods for repairing all types of defects

15   that are anticipated to occur in the multilayer reflective coating. The largest

source of defects appears to be the extrinsic defects nucleated by substrate

imperfections. A smoothing buffer layer can be deposited between the substrate

and the reflective coating to mitigate most of these defects. See P.B. Mirkarimi

and D.G. Stearns, Appl. Phys. Lett. 77, 2243 (2000) and U.S. Patent Application

20   No. 09/454,715, titled "Mitigation of Substrate Defects in Reticles Using

Multilayer Buffer Layers", by P.B. Mirkarimi et al. filed 12/6/99. Extrinsic

defects nucleated near the bottom of the reflective multilayer coating, as well as

all intrinsic defects, will be phase defects. Methods for repairing phase defects in

multilayer coatings, based on locally heating the coating or modifying the

absorber pattern, are currently under development. See. U.S. Patent Application

5   Serial No. 09/669,390, titled "Repair of Localized Defects in Multilayer-Coated

Reticle Blanks for Extreme Ultraviolet Lithography", by the present inventors.

The last category of defect that must be addressed is the extrinsic defect that is

nucleated near or at the top of the reflective coating, and that modulates the

amplitude of the reflected field. The invention that we describe below is a

10   method for repairing this type of amplitude defect.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method to repair an

amplitude defect in a multilayer coating.

15   It is another object of the invention to provide a method for restoring

the local reflectivity of a multilayer coating by physically removing a defect and

leaving a wide, shallow crater that exposes the underlying intact layers.

These and other objects will be apparent to those skilled in the art

based on the disclosure herein.

20   The EUV lithography mask blank consists of a thick substrate coated

with a reflective multilayer film. A particle imbedded near the top of the coating,

or a pit or scratch that damages the coating near the top surface, attenuates the

EUV light and can significantly reduce the local reflectivity of the mask. When

such a feature produces an unacceptable intensity modulation in the lithographic

image, it is considered to be an amplitude defect. The present invention is a

5   method to repair an amplitude defect in the multilayer coating. The invention

exploits the fact that a significant number of layers underneath the amplitude

defect are undamaged. The repair method restores the local reflectivity of the

coating by physically removing the defect and leaving a wide, shallow crater that

exposes the underlying intact layers.

10   The repair method consists of first removing the particle (if a particle

exists) and secondly etching away the damaged region of the multilayer coating

without disturbing the intact underlying layers. The particle is removed by

milling using a high-resolution focused ion beam (FIB) operating near normal

incidence and having a diameter less than 100 nm. The FIB has a gas source

15   (consisting of, for example, He, Ne, Ar, Xe, F, Cl, I, Br), or a liquid metal source

(consisting of, for example, Ga). The FIB is also used for imaging the defect

during the repair process. The removal of the particle leaves a hole in the surface

of the multilayer coating, with collateral damage in the vicinity of the hole due to

implantation and redeposition. In the second step of the repair, the damaged part

20   of the coating is removed by etching using a low-voltage (< 5000 V) ion beam at a

low angle of incidence (< 20 degrees from the coating surface). This could be the

same FIB that is used to remove the particle or a second ion beam. In this step the

ion beam can be relatively large (up to 1 mm diameter) and can be rotated with

respect to the mask to improve the uniformity of the etching process. The low-

voltage, low-angle beam configuration is important because it does not

5 significantly heat the coating during the repair process (the temperature is kept

below 200 °C) and produces minimal damage at the surface. The result of the

repair method is to replace the amplitude defect with a wide (10 μm - 1 mm-

diameter), shallow (typically < 150 nm-depth) crater at the surface of the

reflective multilayer coating that exposes the underlying intact layers and

10 thereby restores the local reflectivity.

In addition to a FIB, it is possible that other tools may be used to

remove the particle and produce a suitable crater in the multilayer coating. For

example, there is a relatively new tool produced by Rave LLC and commercially

available for the repair of absorber layers in patterned masks; this tool is similar

15 to an Atomic Force Microscope but it has the capability to produce a crater of

similar size and shape (in the multilayer coating) to that required by this

invention. This tool could be used for both imaging the defective area and

producing the crater.

This invention has the potential to impact the extreme ultraviolet

20 lithography (EUVL) system currently under joint development between

Lawrence Livermore National Laboratory(LLNL), Sandia National Laboratory,

Lawrence Berkeley Laboratory and the EUV Limited Liability Company which consists of a consortium of companies in private industry. In addition to strong commercial applications, EUVL has the potential to impact government programs such as ASCII.

5   There is a strong commercial driving force for increased miniaturization in electronic devices, and hence an extreme ultraviolet lithography (EUVL) tool has significant commercial potential. To be economically viable this technology requires a nearly defect-free reflective reticle. Commercial integrated circuit manufacturers currently rely on defect-repair

10   techniques to obtain transmission reticles with sufficiently low defect densities; however, these repair techniques cannot be applied to the reflective EUVL reticles. The invention described here is a technique to repair defects in reflective EUVL reticles.

15   BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows the classification of defects that can occur in a EUVL mask.

Figure 2A shows a particle embedded a multilayer reflective coating.

Figure 2B illustrates the removal of the imbedded particle.

Figure 2C shows the result from the process of replacing the hole and the surrounding damaged part of the coating with a large-diameter, shallow crater.

Figure 3 compares the aerial image of a critical-dimension feature on

5   an undamaged coating to the same feature located in the repaired region.

Figure 4 plots the contrast variation due to the changing of the composition of the top layer between Mo and Si as a function of the thickness of the $MoSi_2$ surface layer.

Figure 5 shows the contrast variation as a function of the number of

10   layer pairs that are removed, assuming that the undamaged coating has 60 layer pairs.

Figure 6A shows the variation of the contrast with the maximum depth of the crater for several different values of the radius.

Figure 6B shows the radius of the crater required to achieve a fixed

15   value of contrast, as a function of the maximum depth.

DETAILED DESCRIPTION OF THE INVENTION

An amplitude defect in a reflective multilayer coating can be caused by the imbedding of a particle near or at the top of the coating. The particle reduces

20   the local reflectivity of the coating in two ways:

The particle directly shadows the underlying layers, and thereby reduces the reflected field due to the absorption of light by the particle.

The particle damages the multilayer structure in its vicinity, either in the actual imbedding process, or during the growth of the multilayer around the

5   particle. There is no contribution to the reflected field from the damaged region of the multilayer, and hence the local reflectivity is reduced due to absorption in the damaged region.

Even in the case where the particle does not remain imbedded in the coating, the residual damaged region of the multilayer acts as an amplitude

10   defect. In this case, the defect will physically appear as a pit or scratch in the top of the multilayer coating. It is also important to emphasize that the repair of amplitude defects in the multilayer coating is to be performed on the mask blank, prior to the deposition of the absorber layer.

The basic principle of the repair method is to restore the local

15   reflectivity by removing the particle (if it exists) and the damaged part of the coating, while exposing the intact underlying layers of the multilayer coating. This process must satisfy two constraints. First, the intact underlying layers must not be damaged in the repair process. Second, the repaired region must not produce a significant variation of contrast in the bright field intensity of the

20   lithographic image.

The repair method can be generally divided into two steps as shown

schematically in figures 2A-2C. Figure 2A shows a particle 30 embedded a

multilayer reflective coating 32. In the first step shown in Figure 2B, the

imbedded particle is physically removed by milling using a focused ion beam

5   (FIB). See"Micro-machining using a focused ion beam" R.J. Young, Vacuum 44,

353 (1993), incorporated herein by reference. This step is not necessary if the

defect is a pit or scratch. The FIB has a gas source (consisting of, for example, He,

Ne, Ar, Xe, F, Cl, I, Br), or a liquid metal source (consisting of, for example, Ga).

Using a FIB operated near normal incidence, material can be removed with a

10   depth resolution of 10 nm and a lateral resolution of 100 nm. Typical operating

parameters for a Ga ion source are a beam voltage of 25 keV, a beam current of

40 pA, a beam diameter of 50 nm, and a milling rate of 10 $\mu m^3/nA$-min. An

advantage of this approach is that the FIB can simultaneously provide high-

resolution images of the defect, which is useful for alignment and monitoring of

15   the repair process. A potential problem of using the FIB is that Ga atoms are

implanted into the coating to a depth of approximately 10 nm beneath the

surface. This reduces the optical contrast of the Mo and Si layers directly

underneath the amplitude defect, and requires that these layers be subsequently

removed. A possible way to mitigate the implantation problem is to use a lower

20   beam voltage at the cost of a larger beam diameter.

At this stage there is a small hole 34 in the multilayer coating, as

shown in Figure 2B, having a depth sufficient to remove the imbedded particle.

The remaining structure is still defective because the FIB milling process

produces collateral damage in the vicinity of the hole due to implantation and

5   redeposition. Furthermore, the hole itself will produce a phase perturbation in

the reflected field. To complete the repair of the defect it is necessary to remove

the remaining damaged part of the multilayer coating in the vicinity of the hole,

and to smooth out the contour of the surface of the coating. Specifically, the

second step of the repair process replaces the hole and the surrounding damaged

10   part of the coating with a large-diameter (10 μm – 1 mm-diameter), shallow

(typically < 150 nm-depth) crater 36 as shown in Figure 2C.

The crater is etched in the multilayer coating using a low-voltage (<

5000 V) ion beam at a low angle of incidence (< 20 degrees from the coating

surface). This beam configuration is commonly used for the preparation of thin

15   cross-sectional samples for transmission electron microscopy. See "Precision Ion

Polishing System – A New Instrument For TEM Specimen Preparation Of

Materials" R. Alani and P.R. Swann, Mat. Res. Symp. Proc. 254, 43 (1992),

incorporated herein by reference. It is well known that this technique can

produce a shallow crater of controlled depth having a very smooth and gradual

20   surface slope. The ion beam can be the same as that used for removing the

particle (for example, a Ga-source FIB) or a second ion beam having a gas source

(consisting of, for example, He, Ne, Ar, Xe, F, Cl, I, Br). The beam can be relatively large (up to 1 mm diameter) and can be rotated with respect to the mask to improve the uniformity of the etching process.

The conditions of low voltage and low angle of incidence for the ion beam are critical for avoiding damage to the underlying layers in the multilayer coating. One important requirement is that the temperature of the coating remains below approximately 200 °C throughout the repair process, since higher temperatures can activate structural relaxation at the Mo-Si interfaces. See "Stress, Reflectance, And Temporal Stability Of Sputter Deposited Mo/Si And Mo/Be Multilayer Films For Extreme Ultraviolet Lithography", P.B. Mirkarimi, Opt. Eng. 38, 1246 (1999) It has been shown that etching Si using a Ar ion beam of 4 kV and 1 mA at an grazing angle of 20 degrees increases the temperature of the sample to ~ 85 °C. See D. Bahnck and R. Hull, Mat. Res. Soc. Symp. Proc. 199, 253 (1990) (Title: "Experimental measurement of transmission electron microscope specimen temperature during ion milling"). The temperature increase is expected to be similar for a Mo-Si multilayer coating, and even smaller for lower beam voltage and lower incidence angles.

The other important advantage of using low voltage and low angle of incidence in the etching process is that it minimizes the damage to the layers exposed at the surface of the crater. There is always some mixing induced by the ion beam at the surface. However, studies of Ar ion etching of Si have shown

that the thickness of this damaged surface region is in the range of 1 - 2 nm for a

beam voltage of 2 kV and a grazing angle of 14 degrees. See T. Schuhrke et al.,

Ultramicroscopy 41, 429 (1992) (Title: "Investigation of surface amorphization of

silicon wafers during ion-milling"). In the case of the Mo-Si multilayer coating,

5   the mixing induced by the ion beam is likely to result in a thin surface layer of

$MoSi_2$. This will actually provide a benefit of protecting the pure Mo and Si

layers from oxidation. Alternatively, after the ion milling step a thin (1 –2 nm)

layer of Si can be deposited on top of the exposed multilayer coating in the

repaired region, to limit the oxidation at the surface.

10   <u>Efficacy of the Mask Blank Repair</u>

        In order to evaluate the efficacy of the repair, the effect of the residual

crater on the lithographic image must be considered. The field reflected in the

region of the crater will have a small modulation in phase and amplitude that

will produce a small contrast in the bright field intensity at the wafer. The phase

15   modulation is due to the slope of the surface inside the crater. The amplitude

modulation arises from three effects. First, the reflectivity changes with the

composition of the top layer and hence is modulated along rings within the

surface of the crater, corresponding to the regions where the Mo and Si layers are

alternately exposed. Second, the reflectivity in the crater is reduced due to the

20   absorption of the surface layer, which is assumed to be $MoSi_2$, produced by ion

beam mixing. Third, the reflectivity decreases with the number of bilayers that

are remaining in the multilayer coating, which is a minimum in the bottom of the crater. Since the size of the crater (> 10 μm radius) is much larger than the resolution element, δ, at the mask (δ ~ 200 nm), the residual effect of the repair on the imaging performance will be to cause a local variation in the critical

5   dimension (CD). This can be seen in Figure 3, where the aerial image of a critical-dimension feature on an undamaged coating (line 40) is compared to the same feature located in the repaired region (line 42). Using a simple threshold model for the resist, the CD is determined by the width of the aerial image at the threshold intensity. It is evident that the change in the bright field contrast

10   associated with the repaired region produces an increase in the CD. An estimate of the increase in CD produced by a bright field contrast variation ΔC is,

$$\Delta CD\ (\%) = 0.5\Delta C\ (\%) \tag{1}$$

15   The total budget for the allowable CD variation in EUVL is expected to be 5%. This must be divided among many sources such as flare, pattern error, optical distortion and resist non-uniformity. Hence the CD error budget available to mask defects is more likely to be in the range of ~2%. Using Eq. (1), this implies that the contrast variation in the bright field intensity produced by the

20   repaired region of the multilayer coating should be less than ~4%.

The different contributions to the bright field contrast variation must be considered. The contrast variation due to the changing of the composition of the top layer between Mo and Si is plotted in Figure 4 as a function of the thickness of the $MoSi_2$ surface layer. The undamaged multilayer coating has a

5   top layer of Si (actually SiO_2 after oxidation when exposed to atmosphere). The top layer in the repaired region will alternate between Mo and Si with increasing depth of the crater (see Figure 2C). Figure 4 shows that the contrast variation is different for the Mo (50) and Si (52) top layers, but generally increases with increasing $MoSi_2$ thickness. A similar behavior will occur if there is an oxidized

10   protective layer of Si deposited on the surface of the repaired region.

Another source of contrast variation within the repaired region is the decreased number of layer pairs in the multilayer coating. Figure 5 shows the contrast variation as a function of the number of layer pairs that are removed, assuming that the undamaged coating has 60 layer pairs. It can be seen that this

15   is a fairly small effect; the removal of 20 bilayers results in a contrast variation of less than 1%.

Finally, the shallow crater in the surface of the repaired coating perturbs the phase of the reflected field, resulting in an additional variation of the contrast in the lithographic image. Let us assume that the depth profile of the

20   crater produced by the repair process is Gaussian with a maximum depth of N

bilayers and a radius w. Then the resulting phase perturbation, $\phi(r)$, in the reflected field is given by,

$$\phi(r) = 4\pi N \frac{(n-1)}{n} \exp(-r^2 / w^2) \qquad (1)$$

where λ is the vacuum wavelength of the EUV light and n is the average index of refraction of the multilayer coating (n = 0.97 for Mo/Si). The image intensity at a defocus value of Δz is related to the second derivative of the phase according to [J. M. Cowley, "Diffraction Physics, 2nd ed." (North-Holland, Amsterdam, 1984) p. 61],

$$I(r) = 1 + \Delta z \frac{\lambda}{2\pi} \nabla^2 \phi(r) = 1 + \frac{\lambda^2}{2\pi(NA)^2} \nabla^2 \phi(r) = 1 + \frac{\delta^2}{2\pi} \nabla^2 \phi(r) \qquad (2)$$

Here we have used for the defocus position a value of $\Delta z = \lambda/(NA)^2$ which is twice the conventional depth of focus (this is a very conservative case), and we have defined the resolution element at the mask to be $\delta = \lambda/(NA)$. Substituting into Eq. (2) from Eq. (1) we obtain,

$$I(r) = 1 - 4N\delta^2 \frac{(n-1)}{n} \frac{w^2 - 2r^2}{w^4} \exp(-r^2 / w^2) \qquad (3)$$

The contrast variation in the image intensity is determined from Eq. (3) to be,

$$\Delta C \equiv \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}} = 5.78N \frac{(n-1)}{n} \frac{\delta^2}{w^2} \qquad (4)$$

Now we can estimate the image contrast due to the phase error

produced by the profile of the repaired region for realistic lithographic

parameters. Consider an operating wavelength of 13 nm and a numerical

aperture on the image side of 0.25, which corresponds to a resolution element on

5   the mask of approximately 200 nm. The variation of the contrast with the

maximum depth of the crater is shown in Figure 6A for several different values

of the radius w. It is evident that the contrast increases rapidly with increasing

depth. However, when the radius is 5 μm the contrast remains less than 1 % for a

depth as large as 30 bilayers. Figure 6B shows the radius of the crater required to

10   achieve a fixed value of contrast, as a function of the maximum depth. It is

evident that a crater having a radius greater than 5 μm, or a diameter greater

than 10 μm, will produce a contrast variation in the image intensity of less than 1

%.

Since the total allowable bright field contrast variation produced by

15   the repaired defect is 4%, then the contributions from each of the sources

described above must be limited to around 1%. This sets fairly narrow

specifications for the structure of the repaired multilayer. The consideration of

the modulation of the reflectivity due to the top layer (Figure 4) requires that the

thickness of the $MoSi_2$ surface layer be ~2 nm or less. A protective Si layer

20   deposited on the surface to limit oxidation can be approximately twice as thick,

or up to 4 nm. The dependence of the contrast on the number of bilayers

removed in the repair process restricts the crater to having a maximum depth of

~20 bilayers (Figure 5). A crater that is 20 bilayers deep must have a diameter

greater than 10 μm to keep the phase contrast below the 1% value (Figure 6B). It

is thus concluded that the repair method of removing an amplitude defect and

5   replacing it with a shallow crater is viable in terms of its effect on the

lithographic image. However, the resulting shallow crater is required to have a

maximum depth of 20 bilayers and a minimum diameter of approximately 10

μm. This will maintain the local variation in the CD to be less than 2%, well

within the EUVL error budget. We note that there is no upper limit to the

10   allowable diameter of the crater, and that in practice it could be more convenient

to have the diameter of the crater be considerably larger than 10 μm, even as

large as 1 mm. This would allow the use of a larger-diameter ion beam for the

etching of the crater, i.e. the ion beam diameter could be as large as the crater

diameter of 1 mm.

15   The foregoing description of the invention has been presented for

purposes of illustration and description and is not intended to be exhaustive or

to limit the invention to the precise form disclosed. Many modifications and

variations are possible in light of the above teaching. The embodiments were

chosen and described to best explain the principles of the invention and its

20   practical application to thereby enable others skilled in the art to best use the

invention in various embodiments and with various modifications suited to the

particular use contemplated. The scope of the invention is to be defined by the

following claims.